

# COLLAPSE OF THE PRIMORDIAL GAS CLOUDS IN THE PRESENCE OF UV RADIATION FIELD

Jaroslav Stasielak<sup>1</sup>, Sławomir Stachniewicz<sup>2</sup>, and Marek Kutschera<sup>2,1</sup>

<sup>1</sup>*Institute of Physics, Jagiellonian University, ul. Reymonta 4,  
30-059 Krakow, Poland  
stasiela@th.if.uj.edu.pl*

<sup>2</sup>*Astrophysics Division, H.Niewodniczański Institute of Nuclear Physics,  
ul. Radzikowskiego 152, 31-342 Krakow, Poland  
Sławomir.Stachniewicz@ifj.edu.pl  
Marek.Kutschera@ifj.edu.pl*

**Abstract** Our goal is to study the effects of the UV radiation from the first stars, quasars and hypothetical Super Heavy Dark Matter (SHDM) particle decays on the formation of primordial bound objects in the Universe. We trace the evolution of a spherically symmetric density perturbation in the Lambda Cold Dark Matter and MOND model, solving the frequency-dependent radiative transfer equation, non-equilibrium chemistry, and one-dimensional gas hydrodynamics. We concentrate on the destruction and formation processes of the  $H_2$  molecule, which is the main coolant in the primordial objects.

**Keywords:** Dark matter, structure formation, radiative transfer

## 1. Introduction

The existence of the first objects is a direct consequence of the growth of the primordial density fluctuations. At the beginning, there are linear density perturbations which expand with the overall Hubble flow. Subsequently, these perturbations can grow and form primordial clouds. Clouds with enough density contrast decouple from this flow and start to collapse. The kinetic energy of the infalling gas is dissipated through shocks and the cloud becomes pressure supported. The further evolution of the cloud is determined by its ability to cool sufficiently fast. Clouds which could not cool fast enough will stay in a pressure-supported stage and will not form any stars. The existence of the efficient cooling mechanism is necessary to continue the collapse of the cloud, its subsequent fragmentation and star formation.

In our work we are interested in the first generation of stars which are still forming in the low mass clouds when first luminous objects already exist. These objects are made from the primordial gas so they are metals free. It is simply because the first stars did not have much time to produce them. These objects could be irradiated by the UV and X-rays radiation produced by the first stars, quasars and hypothetical Super Heavy Dark Matter (SHDM) particle decays (Doroshkevich & Naselsky, 2002; Shchekinov & Vasiliev, 2004).

In the absence of metals, the most important cooling mechanism for low-mass primordial clouds is so called ' $H_2$  cooling', i.e. cooling by radiation of excited rotational and vibrational states of  $H_2$  molecule. The presence of initial mass fraction of the molecular hydrogen  $H_2$  of only  $10^{-6}$  is enough to trigger the final collapse of low mass clouds.

However, molecular hydrogen is fragile and can easily be photo-dissociated by photons with energies of 11.26 - 13.6 eV (Lyman and Werner bands) (Shull & Beckwith, 1982). Destruction of the  $H_2$  would stop collapsing of the low mass clouds and decrease star formation rate. On the other hand X-rays radiation can increase production of the  $H_2$  by enhancement of free electrons fraction. From above we see that the UV and X-rays radiation background alters the subsequent growth of cosmic structures. It regulates star formation rate so it has important implication to the re-ionization history of the Universe (Cen, 2003). It is therefore crucial to determine quantitatively the consequences of radiation feedback on the formation of early generation objects.

Feedback of the UV background to the collapse of the spherically symmetric primordial gas cloud was studied by many authors (Tajri & Umemura, 1998; Kitayama & Ikeuchi, 2000; Kitayama, et. al., 2000; Kitayama, et. al., 2001; Omukai, 2001). However their calculation was simplified. They have been using the so called self-shielding function (Draine & Bertoldi, 1996). Our approach includes solving the frequency-dependent radiative transfer equation in the 'exact' way. We also try to check the evolution of the collapsing cloud in the MOND model.

## 2. Description of the code

In the Newtonian case dynamics is governed by the following equations:

$$\frac{dM}{dr} = 4\pi r^2 \rho, \quad (1)$$

$$\frac{dr}{dt} = v, \quad (2)$$

$$\frac{dv}{dt} = -4\pi r^2 \frac{dp}{dM} - \frac{GM(r)}{r^2}, \quad (3)$$

$$\frac{du}{dt} = \frac{p}{\varrho^2} \frac{d\varrho}{dt} + \frac{\Lambda}{\varrho}, \quad (4)$$

where  $r$  is the radius of a sphere of mass  $M$ ,  $u$  is the internal energy per unit mass,  $p$  is the pressure and  $\varrho$  is the mass density. Here eq.(1) is the continuity equation, (2) and (3) give the acceleration and (4) accounts for the energy conservation. The last term in the eq.(4) describes cooling/heating of the gas, with  $\Lambda$  being the energy absorption (emission) rate per unit volume.

$\Lambda$  consist of two parts, that is, the radiative cooling  $\Lambda_{rad}$  and the chemical cooling  $\Lambda_{chem}$ . The former can be written as

$$\Lambda_{rad}(m) = -\varrho \frac{\partial L(m)}{\partial m}. \quad (5)$$

The luminosity  $L(m)$  is obtained by solving radiative transfer equation.

The net chemical cooling rate  $\Lambda_{chem}$  is given by

$$\Lambda_{chem} = \varrho \frac{\partial \epsilon_{chem}}{\partial t} \quad (6)$$

where  $\epsilon_{chem}$  is the chemical binding energy per unit mass.

We use the equation of state of the perfect gas

$$p = (\gamma - 1)\varrho u, \quad (7)$$

where  $\gamma = 5/3$ , as the primordial baryonic matter after recombination is assumed to be composed mainly of monoatomic hydrogen and helium, with the fraction of molecular hydrogen  $H_2$  always less than  $10^{-3}$ .

In case of modified gravity (MOND) we do not include the dark component but it is necessary to modify equation (3). Details are shown in Stachniewicz & Kutschera, 2005.

In the simulations we have used the code described in Stachniewicz & Kutschera, 2001, based on the codes described by Thoul & Weinberg, 1995 and Haiman, Thoul & Loeb, 1996. This is a standard, one-dimensional, second-order accurate Lagrangian finite-difference scheme.

We start our calculations at  $z = 500$  or the end of the radiation-dominated era. We use our own code to calculate the initial chemical composition and initial gas temperature. Initial overdensities may be calculated from the power spectrum which may be obtained e.g. using the CMBFAST program by Seljak & Zaldarriaga, 1996.

We apply initial density profiles in the form of a single spherical Fourier mode used also by Haiman, Thoul & Loeb, 1996

$$\varrho_b(r) = \Omega_b \varrho_c (1 + \delta \frac{\sin kr}{kr}), \quad (8)$$

where  $\varrho_c$  is the critical density of the Universe,  $\varrho_c = 3H^2/8\pi G$  with  $H$  being the actual value of the Hubble parameter. As the initial velocity we use the Hubble velocity:

$$v(r) = Hr. \quad (9)$$

In our calculations we include nine species: H, H<sup>-</sup>, H<sup>+</sup>, He, He<sup>+</sup>, He<sup>++</sup>, H<sub>2</sub>, H<sub>2</sub><sup>+</sup> and e<sup>-</sup>. Full list of relevant chemical reactions, appropriate formulae, reaction, photoionization and photodissociation rates is given in Stachniewicz & Kutschera, 2001.

### 3. Radiative transfer equation in spherical symmetry

In addition to eq. (1) - (4) we solve non-relativistic, time-independent equation for radiation transport in spherical geometry:

$$\mu \frac{\partial I_\nu}{\partial r} + \frac{1 - \mu^2}{r} \frac{\partial I_\nu}{\partial \mu} = \varrho \{j_\nu(r) - \kappa_\nu(r) I_\nu\}, \quad (10)$$

where  $I_\nu = I_\nu(r, \mu)$  is the intensity of radiation of frequency  $\nu$ , at radius  $r$  and in the direction  $\mu = \cos \theta$ , where  $\theta$  is the angle between the outward normal and photon direction.  $j_\nu(r)$  is the emissivity and  $\kappa_\nu(r)$  opacity at radius  $r$ .

Our scheme of solving this equation is similar to method from Mihalas & Mihalas, 1984 and York, 1980. Detailed results will be described in a paper, which is in preparation.

## References

- Cen R., 2003, ApJ 591, 12  
Doroshkevich A. G., Naselsky P. D., 2002, astro-ph/0201212  
Draine B. T., Bertoldi F., 1996, ApJ 468, 269  
Haiman Z., Thoul A. A., Loeb A., 1996, ApJ 464, 523  
Kitayama T., Ikeuchi S., 2000, ApJ 529, 615  
Kitayama T., Tajiri Y., Umemura M., Susa H., Ikeuchi S., 2000, MNRAS 315, L1  
Kitayama T., Susa H., Umemura M., Ikeuchi S., 2001, MNRAS 326, 1353  
Mihalas D., Mihalas B. W., 1984, 'Foundations of Radiation Hydrodynamics', pages 378-381, (New York: Oxford Univ. Press)  
Omukai K., 2001, ApJ 546, 635  
Shull J. M., Beckwith S., 1982, Ann. Rev. Astron. Astrophys. 20, 163  
Seljak U., Zaldarriaga M., 1996, ApJ 469, 437  
Shchekinov Y. A., Vasiliev E. O., 2004, A&A 419, 19  
Stachniewicz S., Kutschera M., 2001, Acta Phys. Pol. B 32, 227  
Stachniewicz S., Kutschera M., 2005, MNRAS 362, 89  
Tajiri Y., Umemura M., 1998, ApJ 502, 59  
Thoul A. A., Weinberg D. H., 1995, ApJ 442, 480  
York H. W., 1980, A&A 86, 286